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Validation of Satellite Rainfall Product (GPM-IMERG) an Bali and Nusa Tenggara: A Comparison of Normal Seasons, El Nino and La Nina Events

Putu Eka Tulistiawan[1,2*], I Wayan Gede Astawa Karang[3], Takahiro Osawa[4,5],
[1]Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG)
[2]Master of Environmental Science Study Program, Universitas Udayana, Bali, Indonesia
[3]Department of Marine Sciences, Faculty of Marine Science and Fisheries, Universitas Udayana, Bali, Indonesia
[4]Yamaguchi University International Collaboration Office (YUICO), Universitas Udayana, Bali, Indonesia
[5]Center for Research and Application of Satellite Remote Sensing (YUCARS) Yamaguchi University, Japan

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Corresponding Author
E-mail: putuekaamg@gmail.com

ABSTRACT

Bali and Nusa Tenggara are regions where monsoonal wind changes and strange interactions between the ocean and atmosphere influence rainfall. The purpose of this research is to evaluate Integrated Multi-Satellite Retrievals for GPM (IMERG) rainfall data using in-situ observations from Bali and Nusa Tenggara, Indonesia, while considering seasonal variations and the El Nino-Southern Oscillation (ENSO) phenomenon. The study combines rainfall data from synoptic stations with rain gauge measurements over ten years, from January 2012 to December 2021, to obtain more accurate verification results. The study's findings indicate that, apart from the transitional seasons, IMERG data provides substantial estimates of monthly rainfall accumulation with low error values for both light and heavy rainfall. The study also reveals that the islands' complexity and topography can impact each province's validation values. The verification results show excellent accuracy in flat terrain areas and moderate elevations, while performance decreases in regions with high altitudes. These findings are significant because IMERG data can estimate rainfall for regions lacking monitoring stations during specific seasons and active ENSO conditions. Thus, this information can serve as a valuable tool to address the issue of data unavailability in hard-to-access areas and contribute to optimizing water resource management and weather-related disaster mitigation.

INTRODUCTION

Bali and Nusa Tenggara are regions where the type of rainfall is influenced by changes in monsoon winds, resulting in distinct wet and dry seasons throughout the year, with the maximum monthly rainfall typically occurring once a year (Tukidi, 2010). The rainy season usually coincides with the west monsoonal wind, which carries significant water vapor from Asia. Conversely, the eastern monsoonal wind transports less water vapor, reducing rainfall in Bali (Nuryanto, 2012; Suprayogi et al., 2016). Furthermore, the El Nino-Southern Oscillation (ENSO) phenomenon, the primary driver of climatic variability in the area, is known to impact Bali, NTB, and NTT (As-Shakur et al., 2007). ENSO events, such as El Nino and La Nina, can significantly influence rainfall patterns and intensity in this region (Athoillah et al., 2017; Yosilia, 2014; Yudistira & Hatahuruk, 2021).

The influence of ENSO/SOI on rainfall varies at each observation point in Bali (As-Syakur et al., 2007), wherein El Nino leads to a reduction in the amount of rainfall, even if it coincides with the dry season, resulting in severe drought (Yosilia, 2014). On the other hand, if La Nina occurs during the rainy season, it can cause excessive rainfall and various issues, including floods and landslides (Yudistira & Hatahuruk, 2021; Athoillah et al., 2017).

The primary source of rainfall data received through direct observations is rain gauges. However, one essential obstacle that must be solved for adequate spatial coverage is the unequal distribution of rain gauges in Bali. Some method to fill the rain gauge gap is using the second data type. One reliable secondary rain measure data is the satellite that measures the rainfall in the atmosphere or surface. Several studies indicated that precipitation satellites could close the data gap by providing the proper correlation and low error rate compared to in-ground observation data. Precipitation and satellite data sources could investigate the spatial patterns of drought-prone regions, notably in the Bali-Nusa Tenggara Islands and other parts of Indonesia (Nuarsa et al., 2015). Among the various satellites used, IMERG has been tested to provide good observation accuracy and the availability of easy-to-access data.

IMERG has an excellent correlation with seasonal rain gauge measurement in tropical areas, but its height is somewhat overestimated in moderate precipitation events between 1–20 mm/day (Tan & Duan, 2017). In high-latitude regions, IMERG could reasonably estimate ground-based precipitation measurements in plains into the diurnal cycle, the variability of average monsoon rainfall, and even some error measurements in mountainous regions (Sungmin & Kirstetter, 2018; Prakash et al., 2018; Ovando et al., 2021). Moreover, research in the southern Tibetan Plateau highlighted the superiority of GPM to TRMM, as well as in Ethiopia, Taiwan, and Brazil, showing the reliable result when validating the IMERG product within situ rain observation sites, as well as Ethiopia, Taiwan (Huang et al., 2018; Sahlu et al., 2016; Salles et al., 2019; Xu et al., 2017).

For the Indonesian region, especially Bali and Nusa Tenggara, rain data from the IMERG satellite can detect monthly rainfall patterns well. Daily, IMERG displays better linearity every month, especially during the transition season, with moderate to solid correlation coefficients, but tends to estimate lower rainfall intensity against observation data (Partharini et al., 2021). The fundamental rainfall data analysis shows a reasonably high correlation between the GPM-IMERG data and the observations data in 31 rain posts in the province of West Nusa Tenggara. It also gets a pretty good score for categorical analysis, with an average accuracy value of 0.75. Based on these results, the GPM-IMERG can be used as a reference for rain data in climate analysis.

Regardless of various research to validate the IMERG data with ground observation, no specific analysis in the Bali and Nusa Tenggara uses much observation data and considers the effect of season, El Nino, and La Nina to analyze the validation results. Previous research mainly utilizes rainfall data from observation stations with few numbers of data during normal conditions. Therefore, it is essential to use rainfall data from observation stations and rain gauges while accounting for the influence of seasons, El Nino, and La Nina occurrences, which might affect precipitation patterns in Bali and Nusa Tenggara, to validate the IMERG data. Integrating extensive observation data is expected to produce more exact verification results. Furthermore, considering seasonal fluctuations and the occurrences of El Nino and La Nina occurrences will provide a more specific depiction of the validation results within each season and during events of atmospheric anomalies such as El Nino and La Nina. As a result, the outcomes of this study will provide estimates of rainfall values during certain seasons, El Nino, and La Nina circumstances in places missing rain observation stations.

RESEARCH METHODS

The study region was located in the Bali and Nusa Tenggara region, Indonesia, between 8.06°S and 12.00°S and between 114.43°E and 125.00°E, with a total area of 73721,81 km2. The rain gauge data will be selected according to the completeness and quality of the data, as shown in Figure 1. Thus, using this field data, IMERG's rain accuracy in Indonesia will be assessed depending on site elevation and three distinct rainfall zones. More information will be provided in the validation technique section.

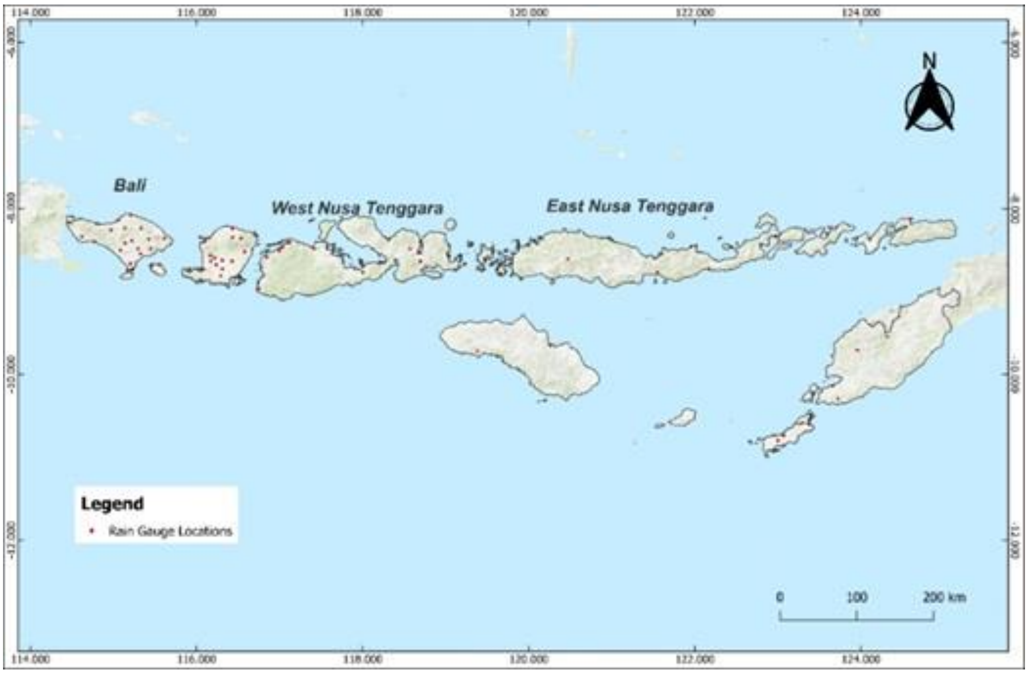


Figure 1. Study Region Where Red Dot Indicates Rain Gauge Position
(Source: BMKG Raingaues Location)

Data used in this consist of:

1. Daily and monthly rainfall data from the IMERG level 3 Final Run dataset spanning January 2012 to December 2021. The data was downloaded from the NASA Earth Data repository available at: https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGM_06/summary?keywords=%22IMERG%20final%22)
2. In situ, monthly rainfall data collected from rain gauge measurement stations provided by BMKG was employed for the study period from January 2012 to December 2021. The dataset comprises 20 observation points in Bali and 40 in Nusa Tenggara, strategically selected to ensure optimal data continuity.
3. The Bali administration map, source from https://www.naturalearthdata.com/was used for spatial reference and contextual analyses in the research.
4. The ENSO event data, represented in the form of Southern Oscillation Index (SOI) Data, was obtained from the Bureau of Meteorology (BOM) Australia, accessible through the following link: http://www.bom.gov.au/climate/enso/outlook.

GPM-IMERG monthly rainfall data was downloaded based on the selected locations. The file subsetting process was performed using OPeNDAP, provided on the NASA website. The data was saved in both NetCDF and ASCII formats. The satellite data projections were carried out using QGIS, ensuring adherence to the WGS84 coordinate reference system. It was plotted on a map with country boundaries to integrate the data spatially. Concurrently, the locations of rain gauges were plotted on the same map to identify the IMERG grids corresponding to each rain gauge location. The corresponding grids were extracted to obtain the relevant time series data. The validation results will be segmented into monthly intervals and further analyzed during La Nina and El Nino occurrences.

The reliability of IMERG rainfall data was assessed through cross-correlation analysis, which aimed to establish a meaningful link between IMERG rainfall and in-situ data. The linear correlation coefficient (r) equation (Feidas, 2010) was employed in the investigation.

$$r = \frac{\sum_{i=1}^{n}(S_i - \underline{S}\,)(G_i - \underline{G})}{(n=1)\sigma_S \sigma_G} \dots\dots\dots (1)$$

Where S_i represents the estimated values (satellite data), G_i represents the reference gauge values, σ_S and σ_G Represent their respective standard deviations, and n is the number of data pairings. The correlation coefficient (r) expresses the degree of linear relationship between the estimated and observed distributions. Furthermore, the Mean Bias Error (MBE) quantifies the systematic component of inaccuracy by quantifying the overestimation or underestimating of gauge data by satellite estimations. On the other hand, Te Root Mean Square Error (RMSE) was employed, despite its susceptibility to high values due to the incorporation of squared deviations from reality, to measure the overall accuracy of the estimations.

The validation values for each month/season are analyzed, considering the seasonal effects in the study regions of Bali and Nusa Tenggara. The parts are divided into four distinct seasons: the dry season May-June-July-August (MJJA), the rainy season November-December-January-February, (NDJF), and two transitional seasons, namely the rainy to dry transitional season March - April (MA) and the dry to rainy transitional season September-October (SO). Additionally, the analysis considers the geographical location of an area concerning the validation results. This aspect involves distinguishing between highlands, lowlands, coasts, and archipelagic regions, which may influence the accuracy and variability of the validation outcomes.

Furthermore, the validation values are subjected to an additional analysis incorporating the influence of the ENSO phenomenon. The validation values during the months characterized by El Nino and La Nina events are analyzed and compared with values during normal conditions. This aims to see whether the ENSO conditions affect the validation of the IMERGS satellite in Bali and Nusa Tenggara. The identification of months affected by ENSO is determined through the SOI values for each respective month, as shown in Table 1.

Table 1. El Nino, La Nina, or Normal Prediction According to SOI Values

SOI Value (in six months period)	Phenomena
below -10	Strong El Nino
-5 s/d -10	Weak to medium El Nino
-5 s/d +5	Normal
+5 s/d +10	Weak to medium La Nina
Above +10	Strong La Nina

(Source: Bureau of Meteorology of Australia, 2012)

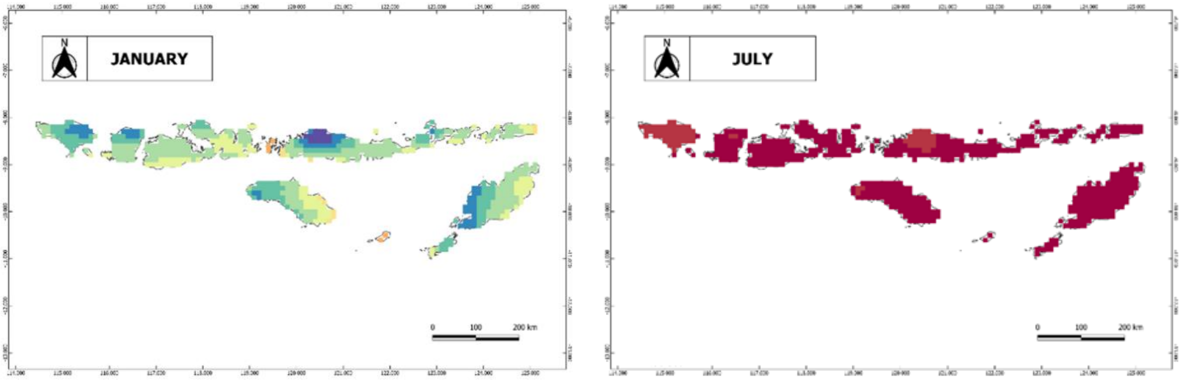
From 2011 to 2020, three El Niño events occurred in 2015, 2018, and 2019 (Nurdiati et al., 2021), while a single La Niña event was identified in 2011 (Bureau of Meteorology, 2012; Yuniasih et al., 2023). For this study, the focus is placed on the El Niño events in 2015 and 2019, along with the La Niña event in 2011, as they align with the data range of GPM-IMERG used in the research. The El Niño event in 2018 was not considered for analysis as it was similar in strength to the 2019 event, and therefore, the latter was deemed more representative. Moreover, the El Niño event of 2015 was particularly robust (Nurdiati et al., 2021), making it a crucial case for investigation.

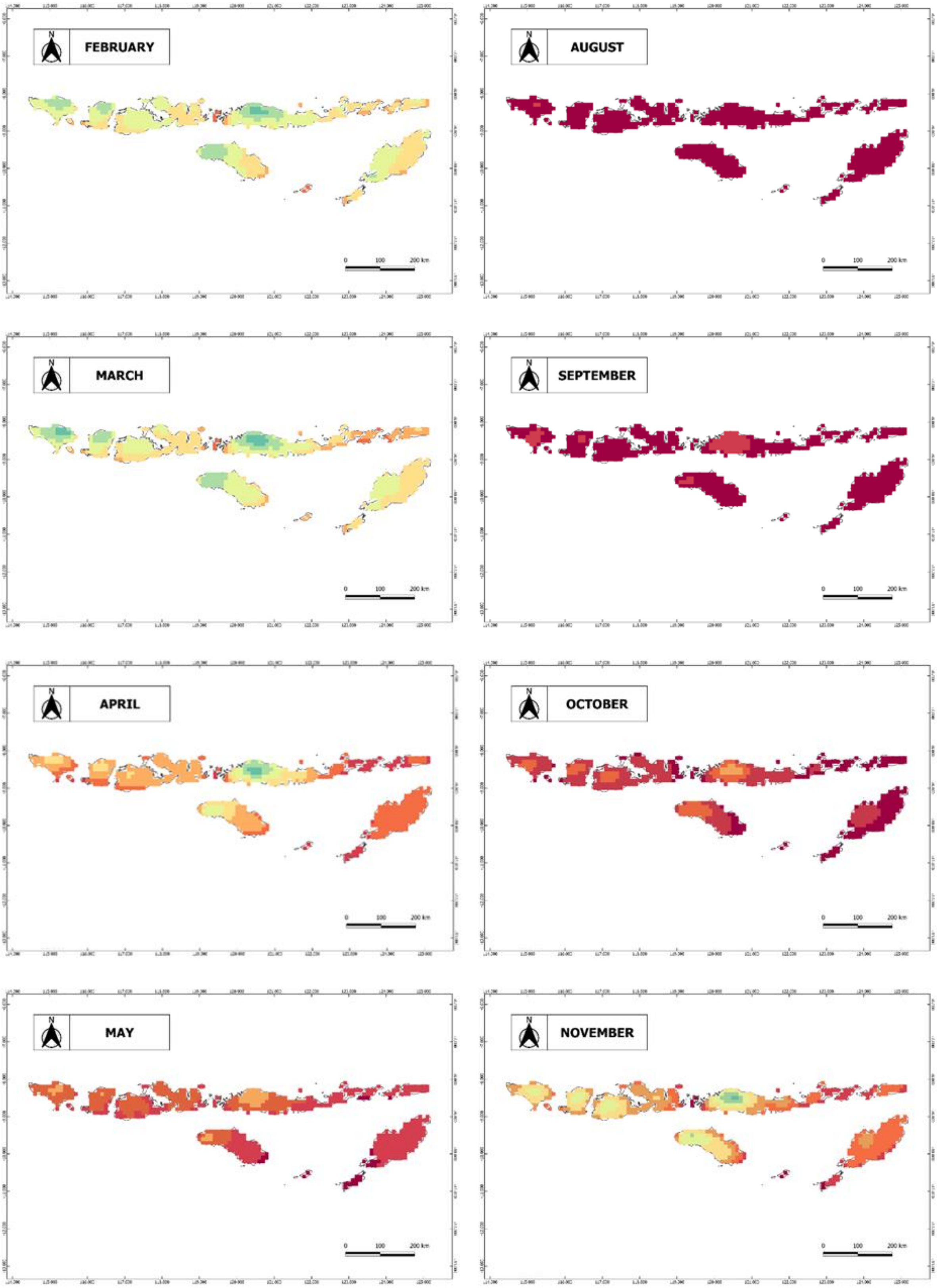
RESULTS AND DISCUSSION

GPM-IMERG Monthly Rainfall data coverage

Monthly rainfall data from the GPM-IMERG satellite is analyzed to determine its value in Bali, NTB, and NTT. This value is then used to observe the rainfall pattern in this area, as shown in Figure 2, The results indicate that the GPM-IMERG satellite is capable of providing rainfall data covering the entire site for each month from January to December, and the monthly rainfall detected by this satellite was from 0 to 450 mm per month. The highest rainfall recorded by the GPM-IMERG satellite in Bali, NTT, and NTB occurred in January, with rainfall intensity values of 250 to 450 mm. Meanwhile, the lowest rainfall was measured in August, with an intensity of less than 100 mm. The GPM-IMERG satellite detects the rainy season in December, January, February, and March and the dry season from June to September. April and May show transitional rainfall patterns from the rainy to the dry season, while October and November show transitional ways from the dry to the rainy season.

The dry season in Bali, NTB (West Nusa Tenggara), and NTT (East Nusa Tenggara) usually occur during the Australian monsoon season, from April to September. According to research by (Sidarta et al., 2015), the dry season in Bali typically occurs between May and October, corresponding to the Australian monsoon season. The article also mentions that the wind blows from the southeast during this season, causing low precipitation in Bali. Similarly, a research article by (Nugraha et al. (2019) indicates that the dry season in Bali occurs from April to September, consistent with the Australian monsoon season. Another study by (Sunarti et al., 2019) states that the dry season in NTT occurs from May to September, which is also consistent with the Australian monsoon season.

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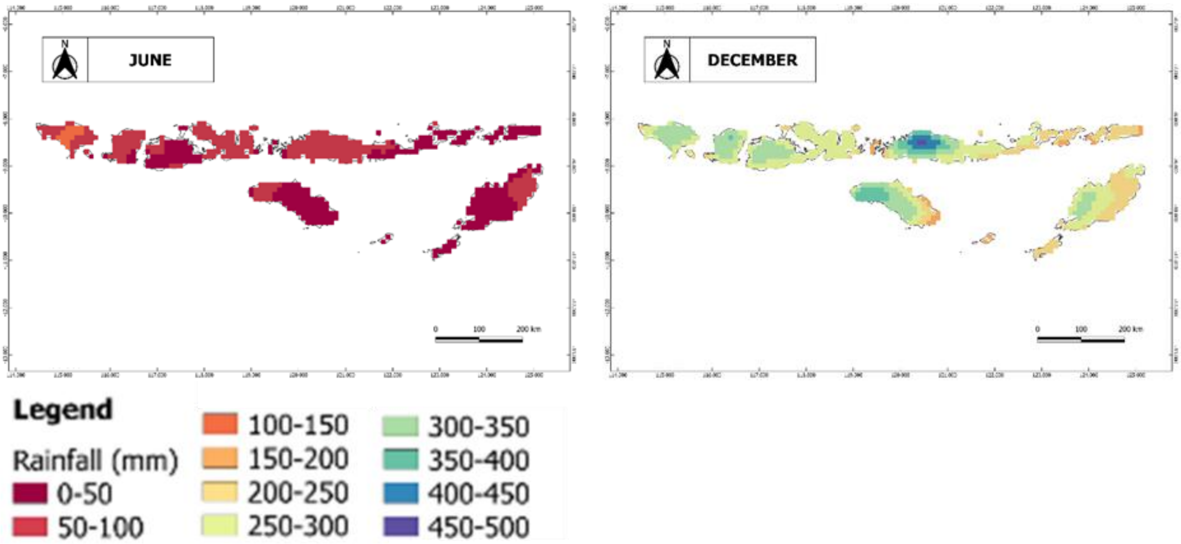


Figure 2. GPM-IMERG Monthly Rainfall data coverage in Bali, NTB, and NTT (Source: IMERG dataset, from the NASA Earth Data repository at: https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGM_06/summary?keywords=%22IMERG%20final%22)

Validating GPM-IMERG Monthly Rainfall data using Rain Gauge Observation data

The temporal analysis reveals the median and average correlation values in Bali, NTB, and NTT from January to December, demonstrating a range from moderate to robust correlation, as shown in Figure 3.

For the province of Bali, the highest correlation value was observed in September, with an average value and the lowest quartile above 0.8 (indicating a robust correlation) and a minimum value exceeding 0.6 (substantial). Subsequently, October, November, and December exhibit a decreasing trend in correlation, with their lowest quartile average values above 0.4, although the maximum value reach 0.5 and higher. Notably, December records the lowest correlation value, with a quartile value ranging from 0.4 to 0.7 and a minimum value below 0.2. Similarly, August also displays a minimum correlation value below 0.2, but its quartile values span from 0.55 to 0.9 (between moderate and very strong).

Regarding NTB and NTT, the highest correlation value was observed in June, with the lowest quartile exceeding 0.8 and the minimum value above 0.6 (substantial to very strong). Subsequently, September displayed a median value above 0.8 and a lowest quartile of more than 0.5. The lowest correlation value was in August, where the highest quartile value was below 0.8, and the median was under 0.6. The lowest minimum value and first quartile value in NTB also occurred in August, but in NTT occurred in July.

Generally, the GPM IMERG satellite exhibited the most accurate estimation of rainfall on a monthly scale. The correlation values ranged from moderate to very strong for most of the months throughout the year in all three provinces. This finding is consistent with the studies conducted by (Yuda et al., 2020; Zang et al., 2022), highlighting the high accuracy of IMERG satellite rainfall data on monthly to seasonal timescales. Moreover, the research conducted by (Liu et al., 2020) showed that IMERG satellite rainfall data performed exceptionally well on daily, weekly, and seasonal time scales, with only minimal inaccurate values observed for light and heavy rainfall. Even though IMERG shows a low correlation value during the transition season between rain and dry, or vice versa, the satellite still provides a high correlation value when calculating the monthly accumulation of rainfall (Azka et al., 2018 Pandiangan et al., 2022).

The dry season's low rainfall intensity led to reduced error value in this study, aligning with previous research utilizing various satellite products within Indonesia, where the RMSE values were notably lower during the dry season (Fatkhuroyan et al., 2018; Pandiangan et al., 2022). Conversely, the highest error values were observed during the peak of the rainy season in an area with monsoonal rainfall patterns (Parwati, 2015). Such sites exhibited underestimated or overestimated values due to disparities between estimations and ground observations. These findings echoed the results of Liu et al. (2020), who reported that IMERG tended to underestimate the frequency of light and heavy rainfall events while overestimating the frequency of moderate rainfall events. Moreover, (Mohammed et al., 2020; Yuda et al., 2020) stated that IMERGS displayed better performance, low bias, and low error when the rainfall rate was low.

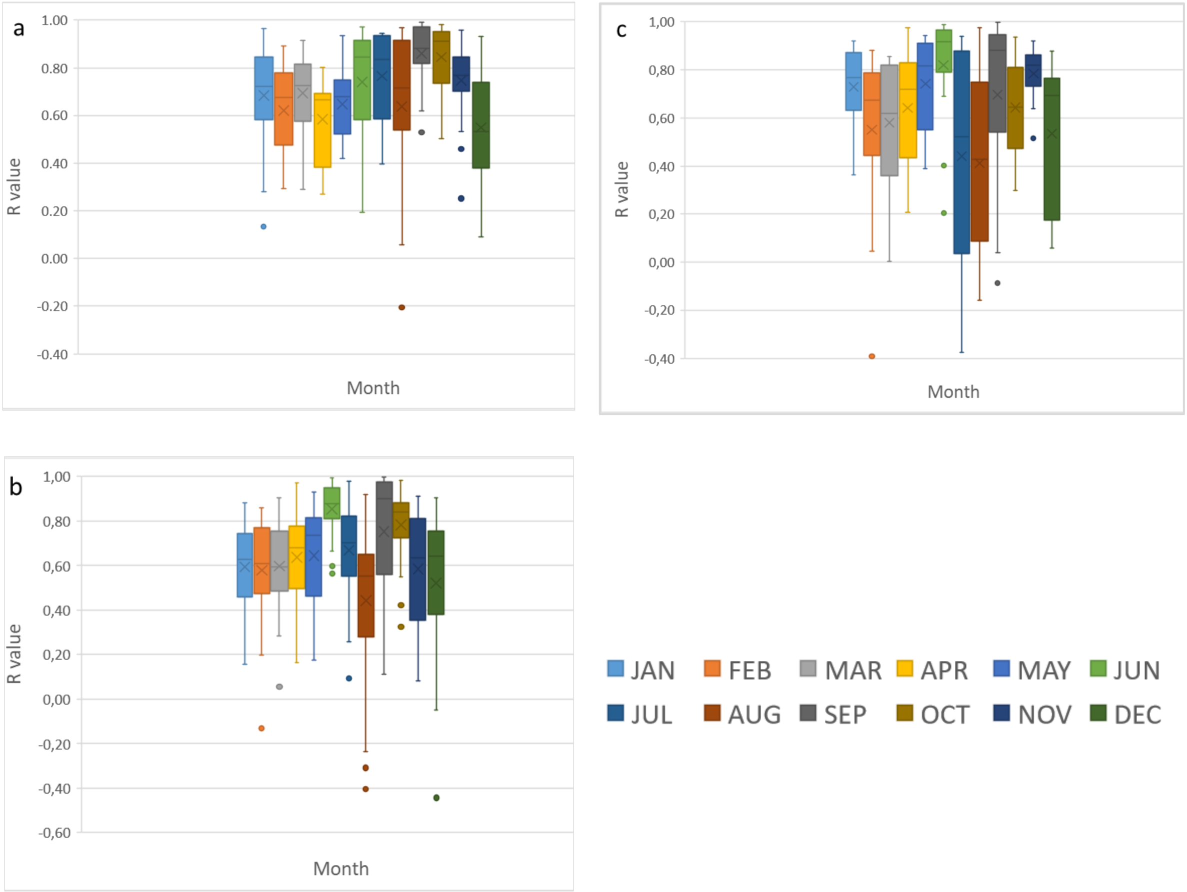


Figure 3. Monthly correlation (R) value between GPM-IMERG and Rain Gauge in (a) Bali, (b) NTB, and (c) NTT (Source: IMERG dataset, BMKG Ground Observation station and the Bureau of Meteorology (BOM) Australia)

The spatial analysis assessed the validation value in each province (Bali, NTB, NTT) from January to December, with the results for the monthly average presented in Figure 4.

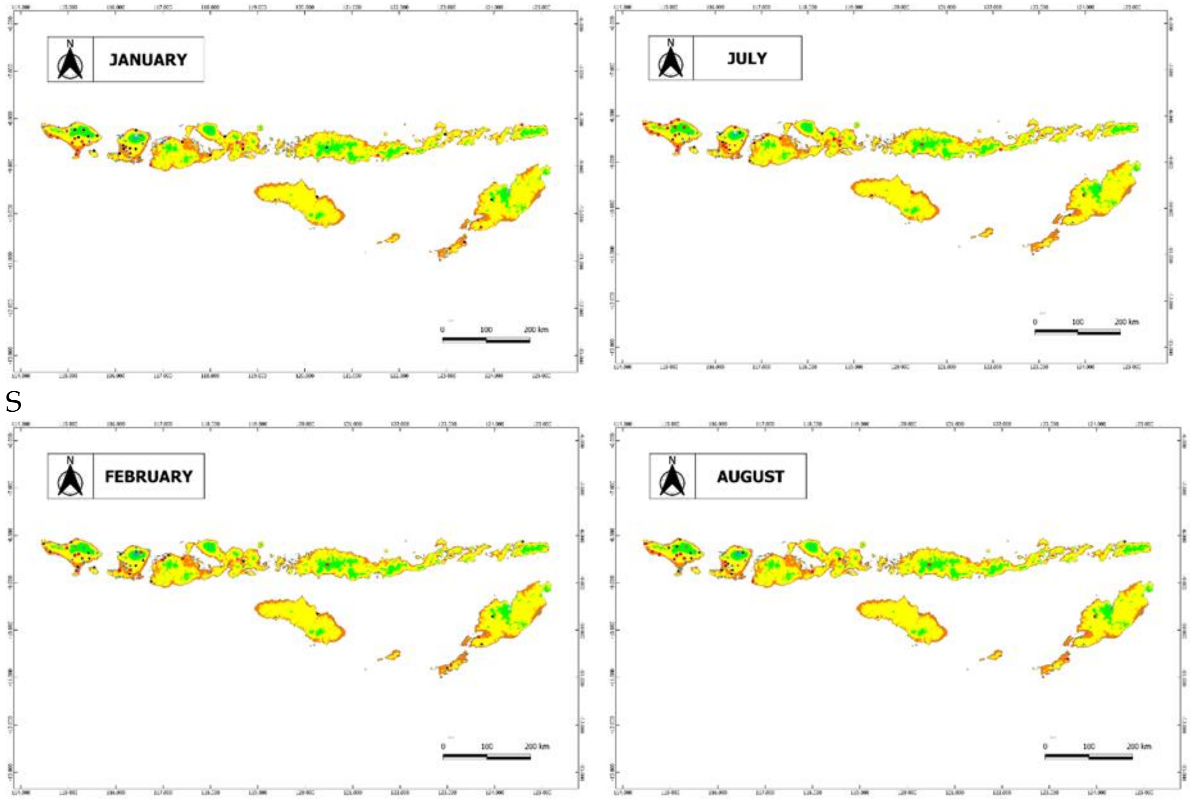
In Bali, a consistently robust correlation between ground and IMERGS rainfall measurements was observed throughout most of the year except in December, February, April, and May. Also, Figure 4 displays the most extensive coverage area of robust correlation in Bali in September and October. Fragile correlation values between ground observation and IMERGS rainfall data were less prevalent in Bali, in contracts to moderate, intense, and extreme correlation values.

West Nusa Tenggara (NTB) had an extreme correlation value almost all year (except in December, January, and February). The strong correlation was particularly prominent on Sumbawa Island. Throughout the year, NTB predominantly exhibited moderate to strong correlation values, occurring consistently each month. Meanwhile, very weak to weak correlation values were present for most of the year, except during June and October (Figure 4).

The correlation analysis for East Nusa Tenggara (NTT) revealed varying spatial distributions of weak, moderate, strong, and powerful correlations across the province throughout the year (Figure 4). A very weak correlation was observed for approximately half of the year. The northern part of NTT (Flores Island and small islands to the east) featured a dominant spatial distribution of extreme correlation values occurring in 11 months, with April being the exception.

The difference in rainfall intensity most likely caused the observed variations in validation values within specific areas. IMERG's performance in determining the rainfall intensity in tropical regions, as (Azka et al., 2018) highlighted, might contribute to such variations. Furthermore, according to the research by (Mohammed et al., 2020), the regions with low density of rain gauge stations reduce the proper estimation of satellite products and tend to increase the error of the estimation rainfall value.

The high correlation values observed in most Bali, NTB, and NTT indicate that GPM IMERG provides a reliable rainfall estimation. These findings are further supported by the research conducted by (Liu et al., 2020; Asferizal et al., 2022), both of which highlight that IMERG products exhibited better performance in Bali and Nusa Tenggara than other satellite rainfall products.



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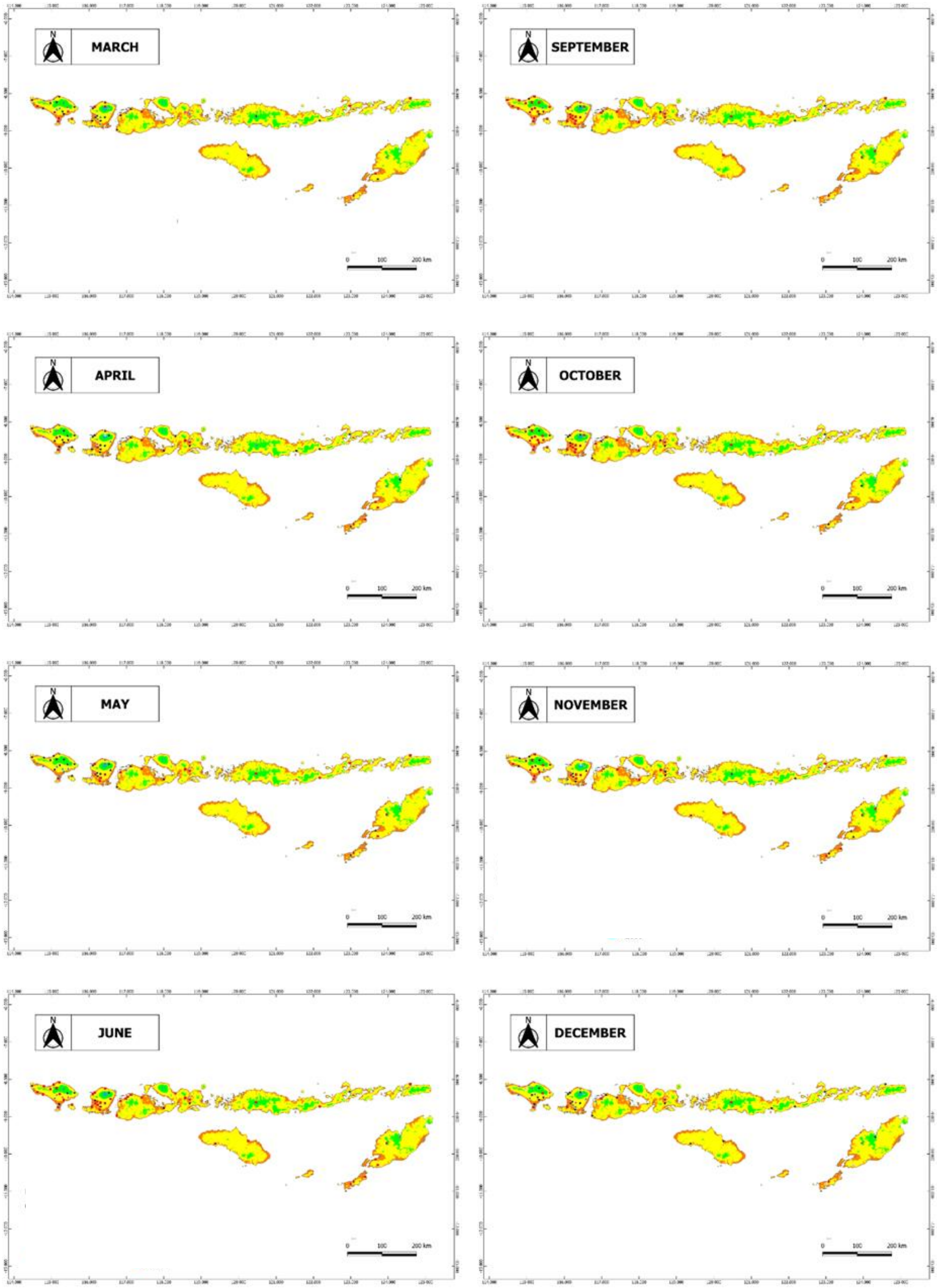

Figure 4. Spatial Correlation Value between GPM-IMERG and Rain Gauge in Bali, NTB and NTT (Source: IMERG dataset, BMKG Ground Observation station and the Bureau of Meteorology (BOM) Australia)

Analyzing the effect of various types of ENSO on the IMERG rainfall data

The validation Value between ground observation and IMERGS rainfall data was analyzed during anomaly atmospheric conditions such as ENSO phenomena. It is to find the effect of this event on the pattern and accuracy of IMERGS data to ground observation data, as shown in Figure 5.

The Correlation value during the Enso event in Bali, NTB, and NTT was always lower than the average 10-year correlation value with or without the ENSO year included, and its value varied according to the type of ENSO and year of the event. Moreover, the average 10-year correlation value with the ENSO year was higher than the ENSO year excluded. In Bali, NTB, and NTT, La Nina 2011 event caused the correlation value to reach the lowest value compared to both El Nino events. In Bali, the second lowest correlation value occurred during El Nino 2015, and the highest correlation value of all ENSO events was uncured during El Nino 2019. However, NTB and NTT El Nino 2015 caused the highest correlation value, and El Nino 2019 generated the second lowest correlation value of ENSO events.

During the ENSO event in Bali, NTB, and NTT, the correlation value decreased in most observation points from -1% to -38%, even though a few observations showed an increase in correlation value from 1% to 18%. La Nina 2011, on average, caused the highest decrease in all three provinces, followed by El Nino 2019 and El Nino 2015.

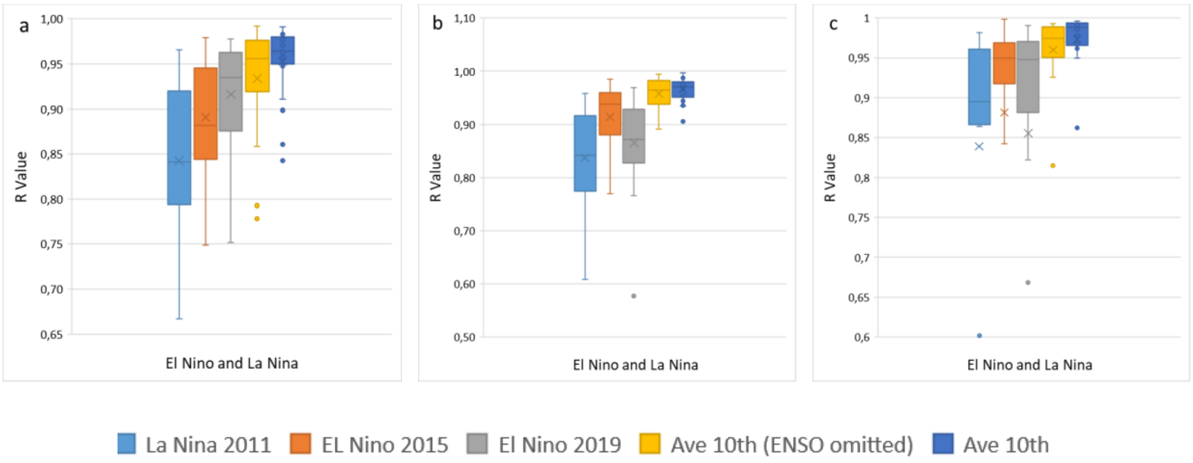

Figure 5. Temporal Correlation Value during La Nina and El Nino between GPM-IMERG and Rain Gauge in (a) Bali, (b) NTB, and (c) NTT (Source: IMERG dataset, BMKG Ground Observation station and the Bureau of Meteorology (BOM) Australia)

During La Nina 2011, as shown in Figure 6, the correlation value dropped from very strong to firm in a few areas of Bali, NTB, and NTT. Most of the site that experienced a correlation value dropped was located in a coastal area close to straits. For instance, a small room in North and Southwest Bali, a large area in Southeast Bali, Northwest Lombok, Northwest Sumbawa, Southwest of Sumbawa, and Central North of Timor Island. However, a few places, such as Central Timor Island, were situated in the island's center with strong correlation values.

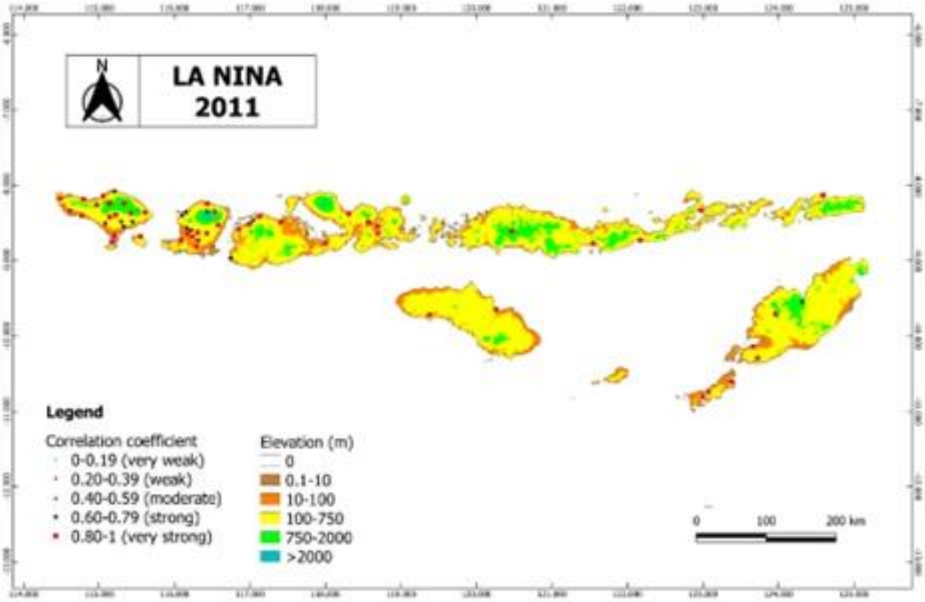

Figure 6. Spatial Correlation Value during La Nina 2011 between GPM-IMERG and Rain Gauge in Bali, NTB and NTT (Source: IMERG dataset, BMKG Ground Observation station and the Bureau of Meteorology (BOM) Australia)

Figure 7. shows that El Nino 2015 slightly decreased the correlation value in Bali, NTB, and NTT. Only a small area in Central Bali, Northwest, and Central Sumbawa Island had a decreasing correlation value from very strong to strong, while the rest of the site was still in powerful value.

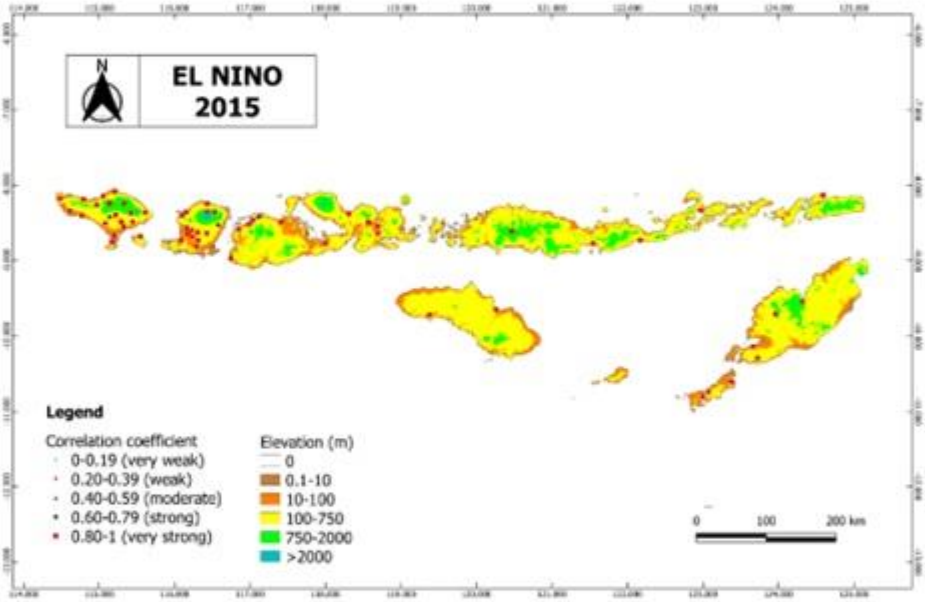

Figure 7. Spatial Correlation Value during El Nino 2015 between GPM-IMERG and Rain Gauge in Bali, NTB and NTT (Source: IMERG dataset, BMKG Ground Observation station and the Bureau of Meteorology (BOM) Australia)

Several areas in Bali, NTB, and NTT were affected by El Nino 2019 regarding the reduction of the correlation value. The effect was considered weak in Bali Island since only a small area in north Bali experienced a drop in correlation value from very strong to strong compared to normal conditions. However, in NTB and NTT, two coastal regions had strong correlation values (lower than normal conditions), such as Central-east of Sumbawa Island and Central-north of Timor Island (Figure 8.).

At the time of the ENSO event, Bali, NTB, and NTT generally had a uniform correlation value between the rainfall from ground observation and IMERG satellite in most areas. This shows that the effects of El Nino and La Nina in these three provinces are almost similar, which follows the research from Tanggang et al. (2018), which states that for the maritime continent region, such as the area located in the southern part of Indonesia, it has the same response to ENSO events. Then, the validation values that did not change much from normal in the 2015 and 2019 El Nino events were caused by the El Nino events having the most significant effect on the dry season (Athoillah et al., 2017).

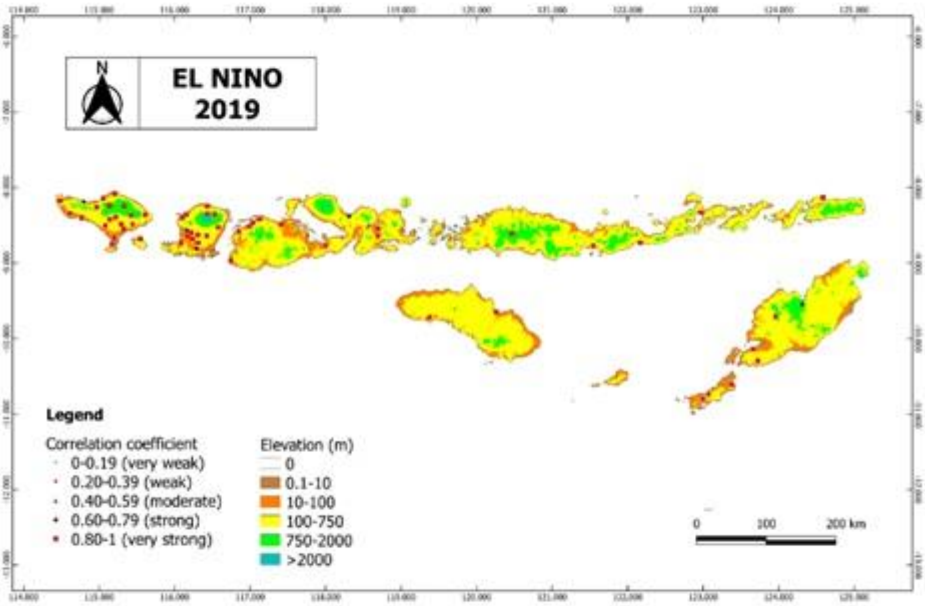

Figure 8. Spatial Correlation Value during El Nino 2019 between GPM-IMERG and Rain Gauge in (a) Bali, (b) NTB, and (c) NTT (Source: IMERG dataset, BMKG Ground Observation station and the Bureau of Meteorology (BOM) Australia)

CONCLUSION

In conclusion, the study reveals significant findings regarding the correlation between ground observations and IMERG satellite rainfall data in Bali, NTB, and NTT. The highest correlation values were observed in June for NTB and NTT, while in September in Bali. The dry season occurs from April to September, resulting in low precipitation due to southeast winds.

The IMERG data showed a strong correlation and provided reliable rainfall estimations for most areas, except during certain months and transition seasons. The analyses also demonstrated that the IMERG Satellite could accurately capture the yearly rainfall pattern and direction of ground observation data.

However, during the ENSO events, fluctuations in correlation values were observed in coastal areas near straits. El Nino events negatively impacted the dry season, reducing rainfall validation values. In contrast, La Nina events caused an increase in rainfall, resulting in reduced correlation values. The impact of ENSO events on rainfall validation values varied depending on the event's strength and the season.

The study emphasizes the importance of accurate rainfall data validation for improved water resource management in Bali, NTB, and NTT. Understanding the fluctuations in rainfall patterns caused by El Nino and La Nina enables better water allocation planning and preparation for water shortages during droughts. It ensures sustainable water supplies for agriculture, tourism, and local communities (Rahma & Harisuseno, 2019). These findings contribute to the effective management of water resources in the region and aid in mitigating the impacts of extreme climate events.

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